Power Measurements and Transformer Behavior During DTRA MHD-E3/GIC Tests

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by

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There are several definitions of electric power. Each is useful and provides valuable insight when properly applied and interpreted.

- **Instantaneous Power** $p(t) = v(t) * i(t)$. Physics based. Applies to all situations. It is the basis for all other power definitions.

- **Three-Phase Instantaneous Power** $p_{abc}(t) = p_a(t) + p_b(t) + p_c(t)$. Useful in showing the total power flowing into or out of a three-phase transformer or load.

Given the definition of instantaneous power, simplifications can be made to more easily analyze and understand common “real world” situations by defining

- **Average Power**. Average over one or more integer cycles of v(t), i(t).
- **Real Power, Reactive (or Imaginary) Power, Complex Power, Power Factor, and Power Triangle**. Appropriate and timesaving when analyzing steady-state, single-frequency AC power systems. Work in conjunction with phasor analysis and root mean squared (RMS) voltage and current.
- **Harmonic Power**. Parasitic power produced by nonlinearities such as power electronic loads or saturated transformers. Useful in cases with periodic nonsinusoidal v(t) and i(t). Fourier series yields the harmonic components of v(t) and i(t). Phasor analysis applies to each harmonic. Work in conjunction with total harmonic distortion Vthd and Ithd.

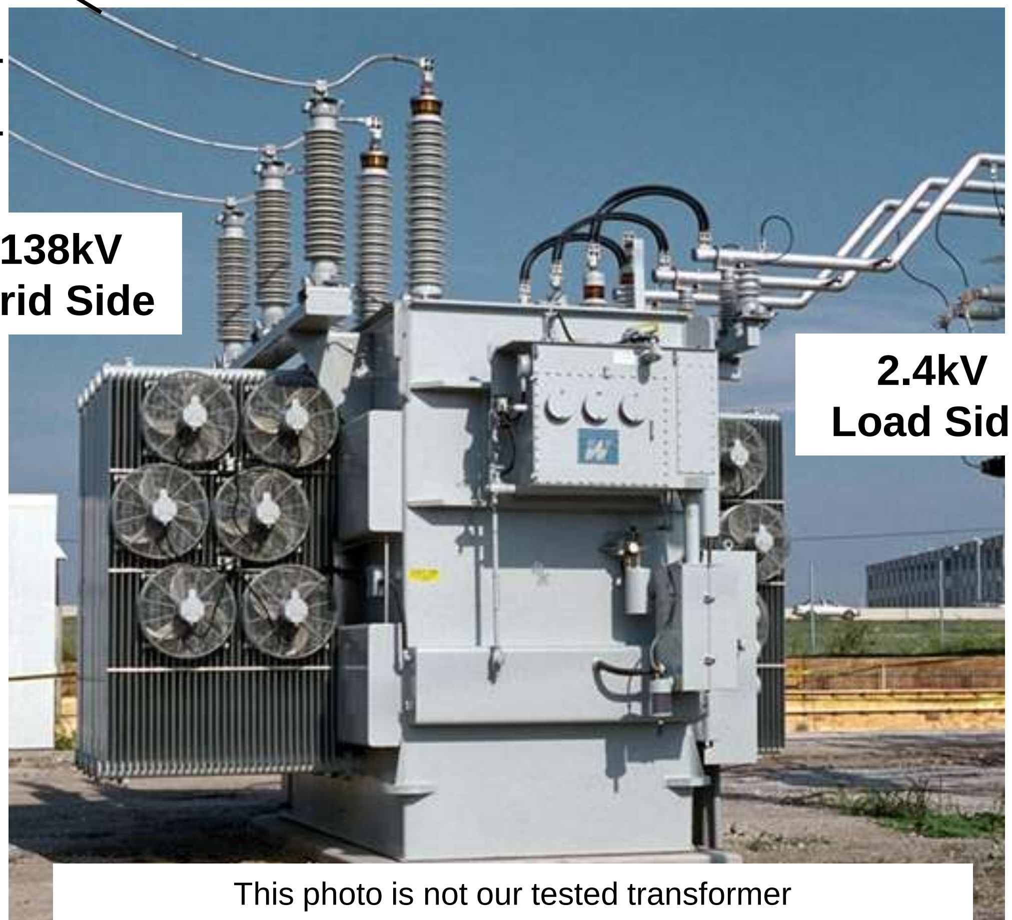
Our Tests - Instantaneous Voltages and Currents are Measured on Both Sides.
Then, Off-Line, Instantaneous and Average Powers are Calculated and Analyzed.

Pin = Va*Ia + Vb*Ib + Vc*Ic

Pout = va*ia + vb*ib + vc*ic

Ploss = Pin – Pout

+Va Ia
+Vb Ib
+Vc Ic



This photo is not our tested transformer

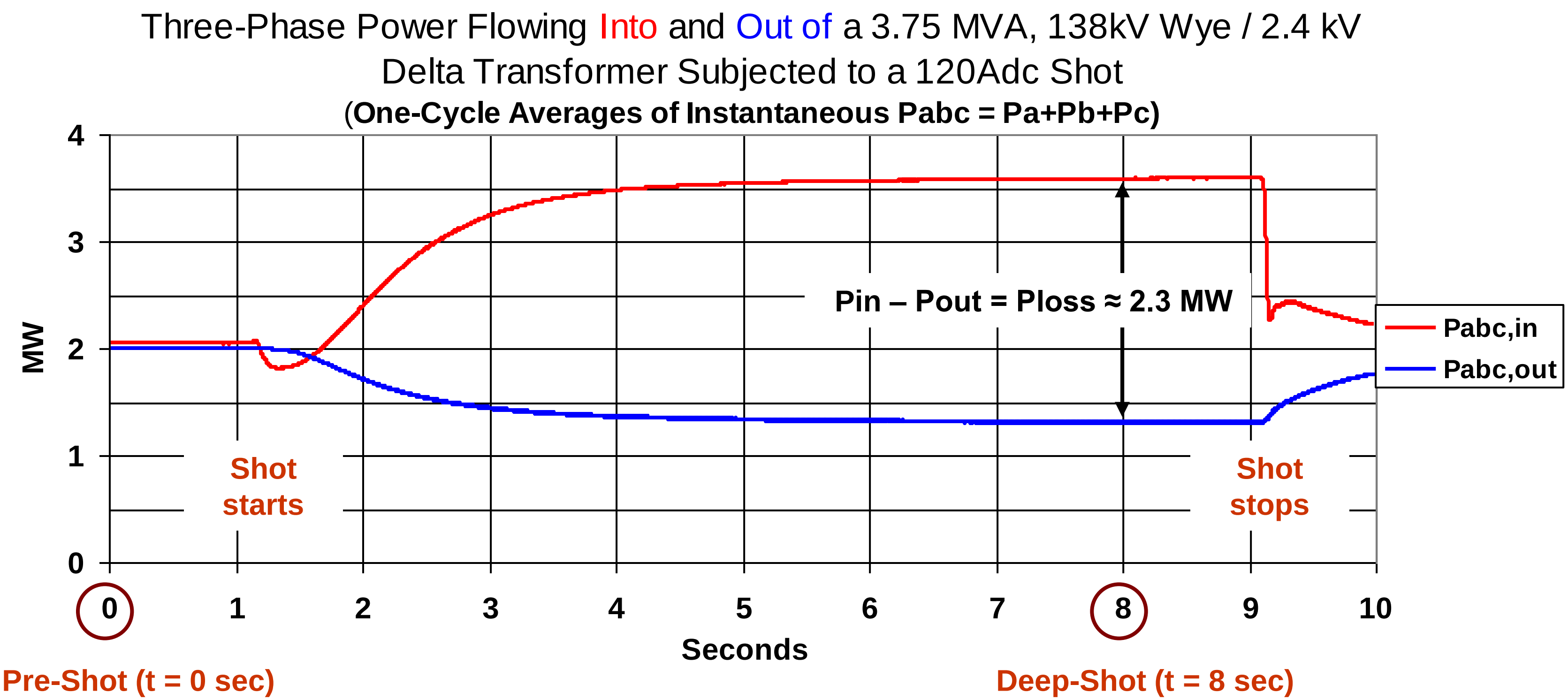
+va, +vb, +vc,
ia, ib, ic

Voltage Reference is Ground

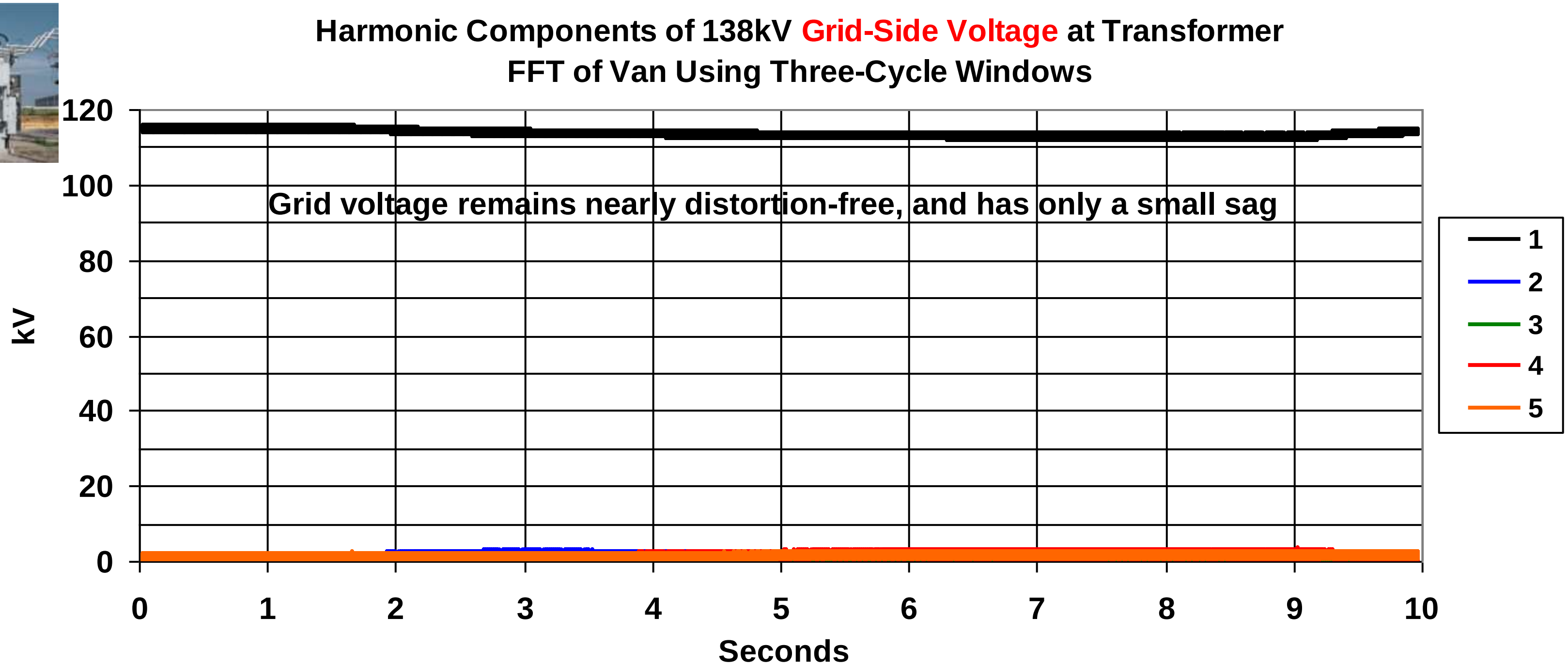
One-cycle averages of pabc INTO transformer

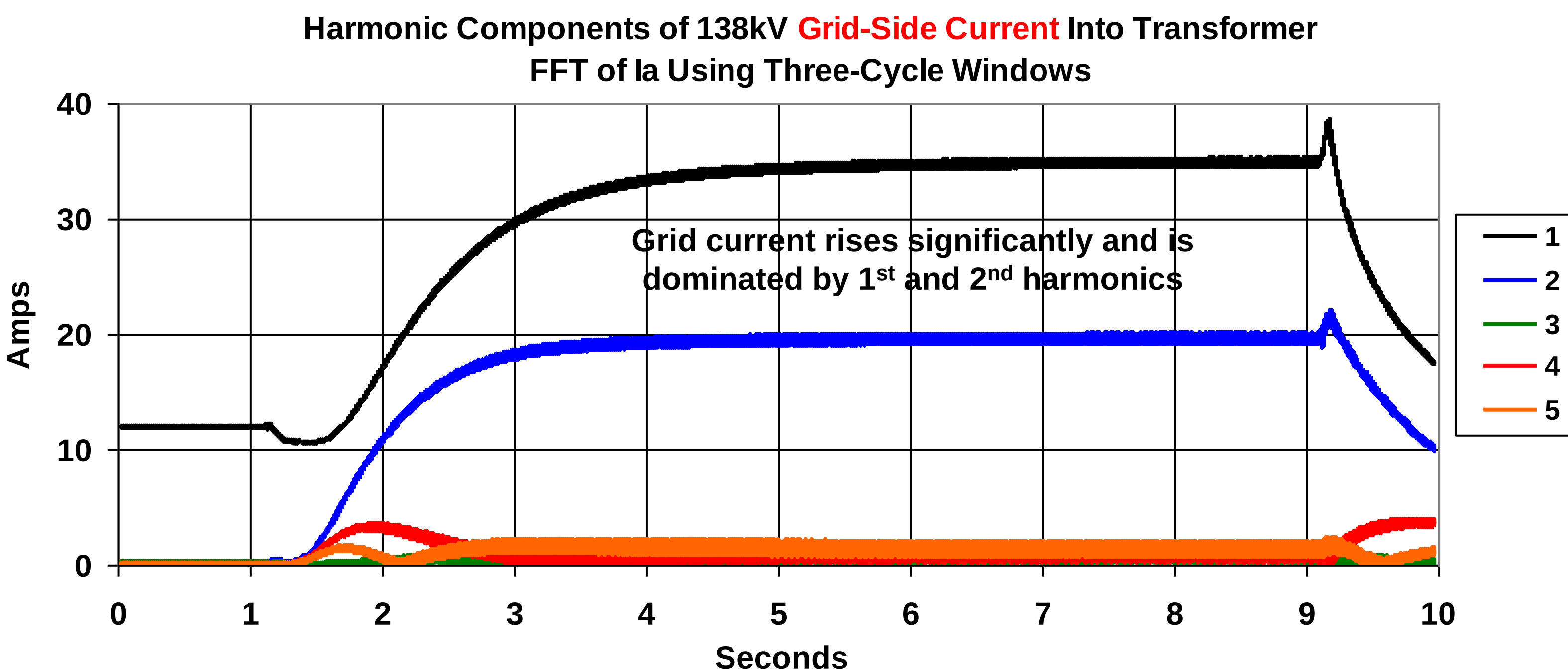
One-cycle averages of pabc OUT OF transformer

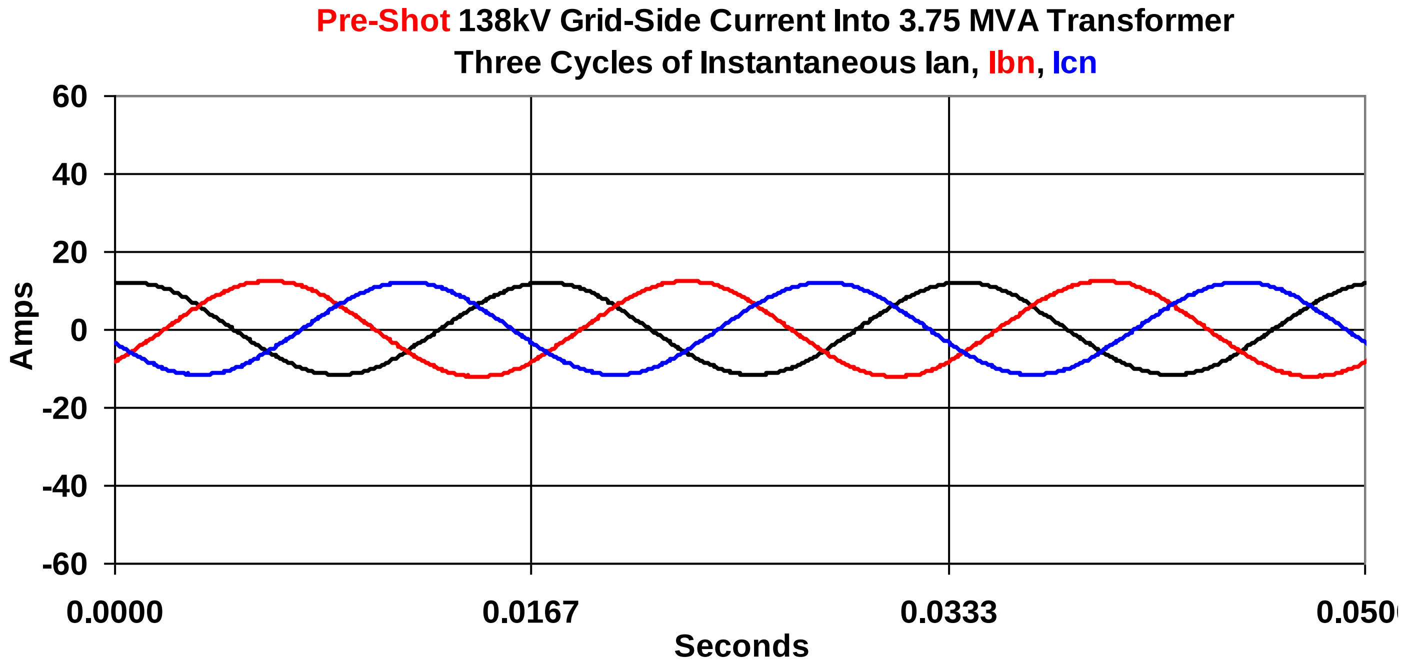
Impact of 120Adc Shot (40Adc each phase) Into the 138kV Windings

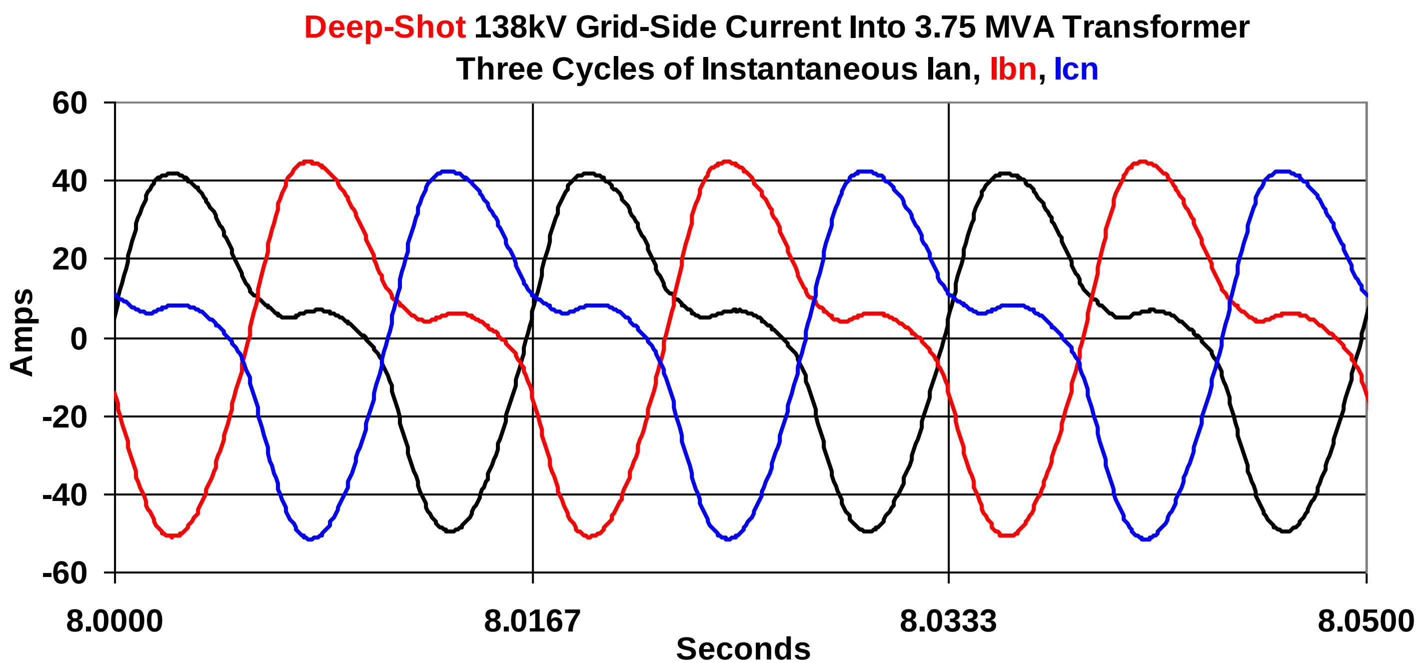


Transformer losses during the shot are approximately 60% of transformer rated power, and about 60-to-100 times normal losses

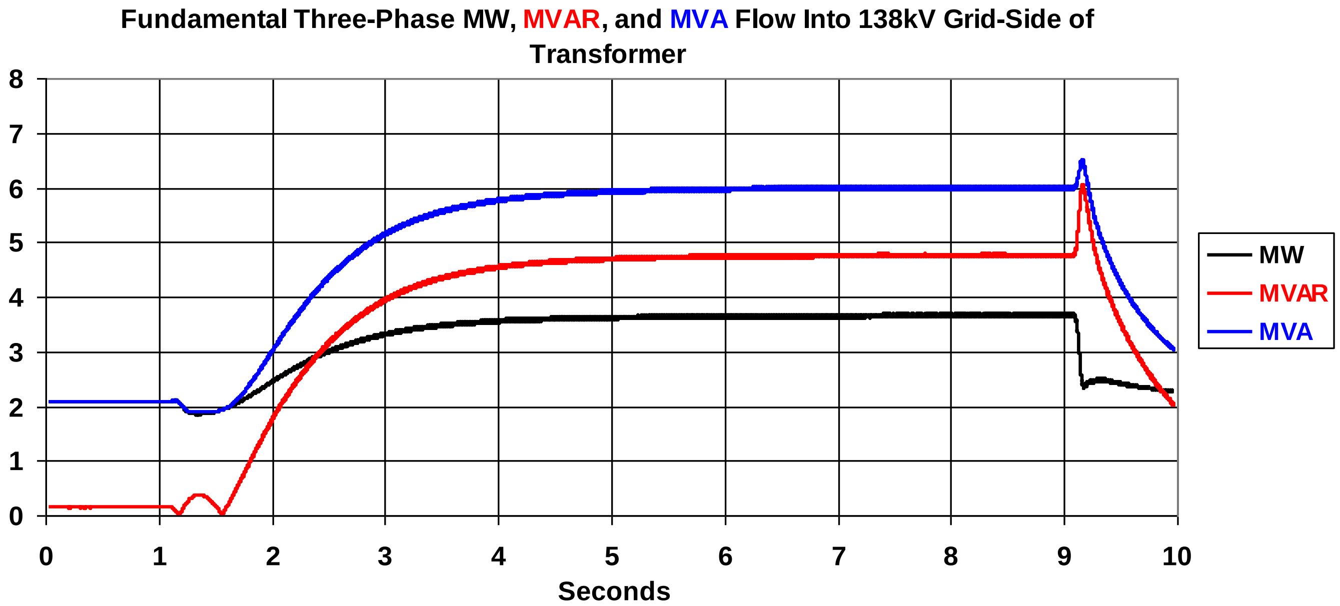

Harmonic Components of 138kV Grid-Side Voltage at Transformer
FFT of Van Using Three-Cycle Windows
Grid voltage remains nearly distortion-free, and has only a small sag
kV
Seconds
0
20
40
60
80
100
120
0
1
2
3
4
5
6
7
8
9
10
1
2
3
4
5

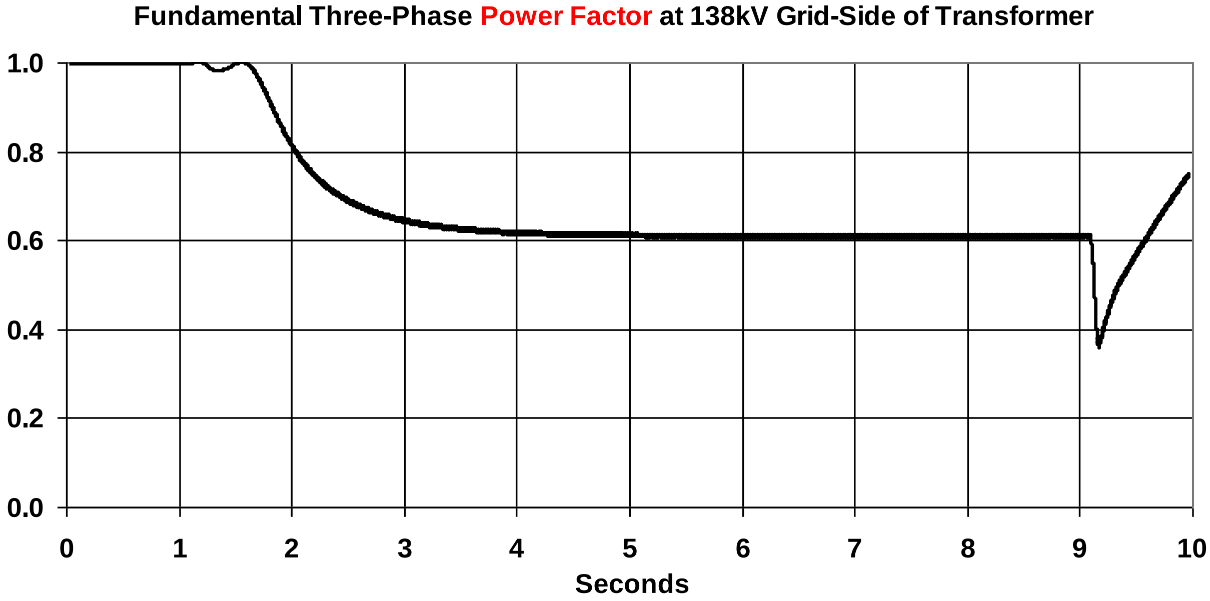

Harmonic Components of 138kV Grid-Side Current Into Transformer
FFT of Ia Using Three-Cycle Windows
Grid current rises significantly and is
dominated by 1st and 2nd harmonics
Amps
Seconds
0
10
20
30
40
0
1
2
3
4
5
6
7
8
9
10
1
2
3
4
5

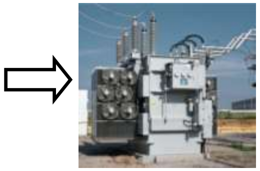

Pre-Shot 138kV Grid-Side Current Into 3.75 MVA Transformer
Three Cycles of Instantaneous Ian, Ibn, Icn
Amps
60
40
20
0
-20
-40
-60
0.0000
0.0167
0.0333
Seconds

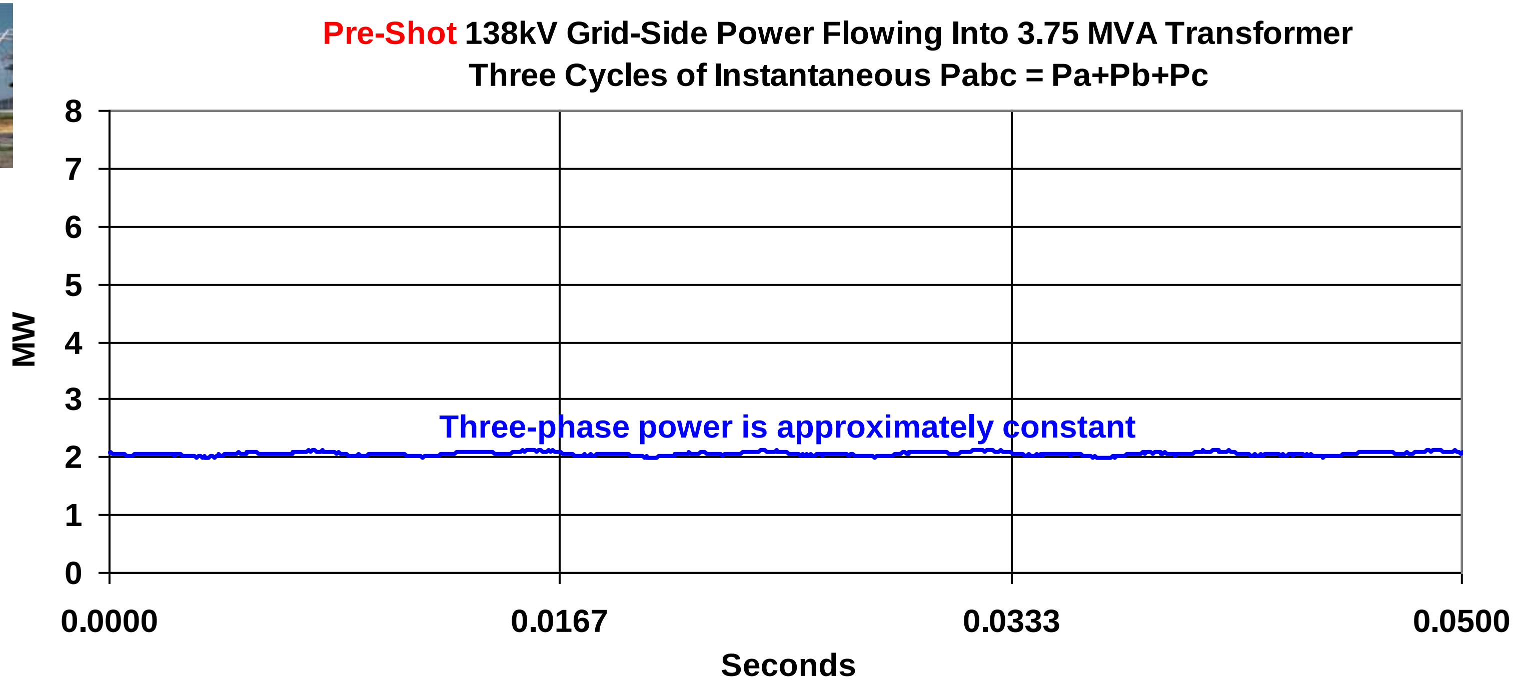

Deep-Shot 138kV Grid-Side Current Into 3.75 MVA Transformer
Three Cycles of Instantaneous Ian, Ibn, Icn
Amps
60
40
20
0
-20
-40
-60
8.0000
8.0167
8.0333
8.0500
Seconds

From a Purely 60 Hz Viewpoint, Here are the Power Characteristics of the 138kV Transformer Under Test

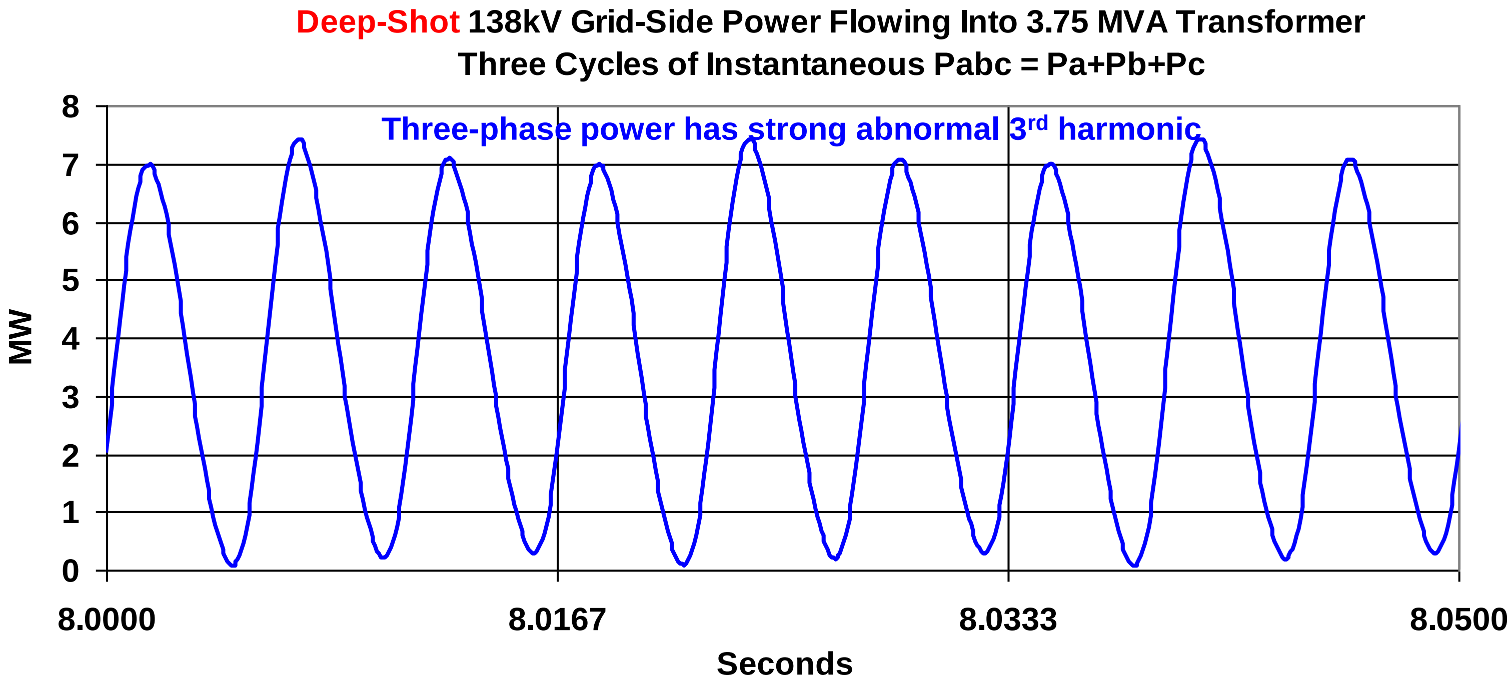






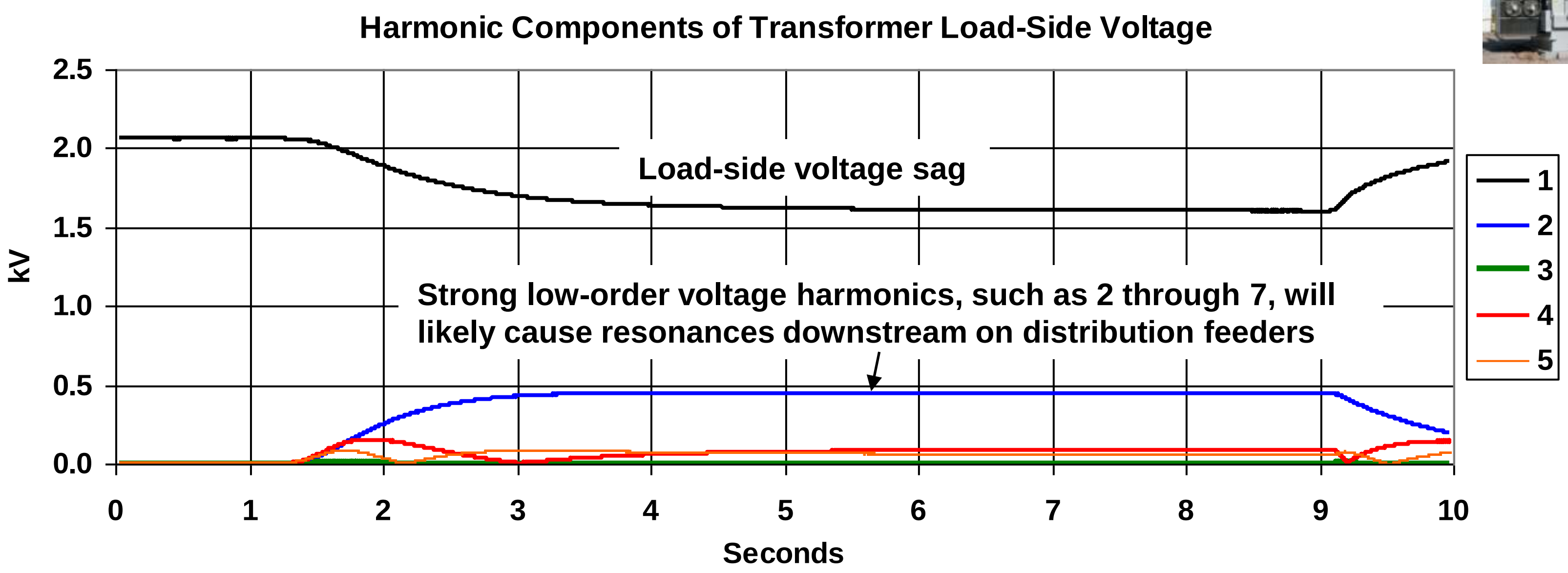


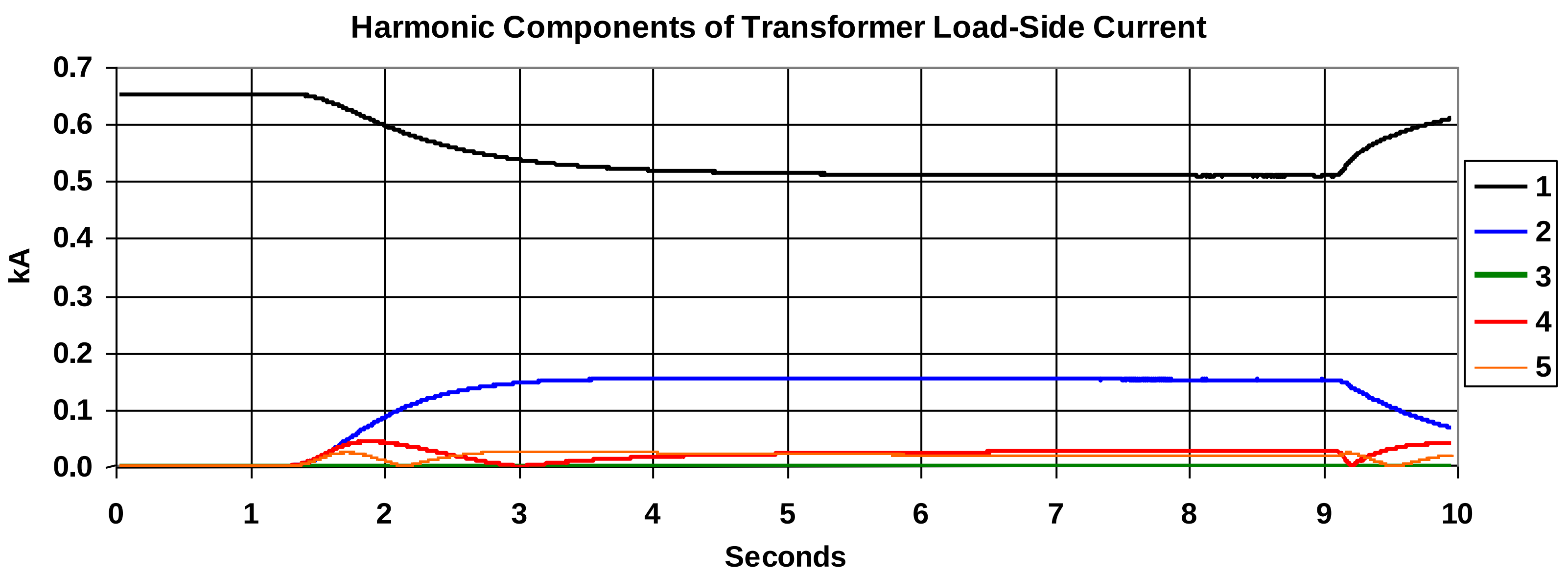
Pre-Shot 138kV Grid-Side Power Flowing Into 3.75 MVA Transformer
Three Cycles of Instantaneous Pabc = Pa+Pb+Pc
Three-phase power is approximately constant
MW
8
7
6
5
4
3
2
1
0
0.0000
0.0167
0.0333
0.0500
Seconds



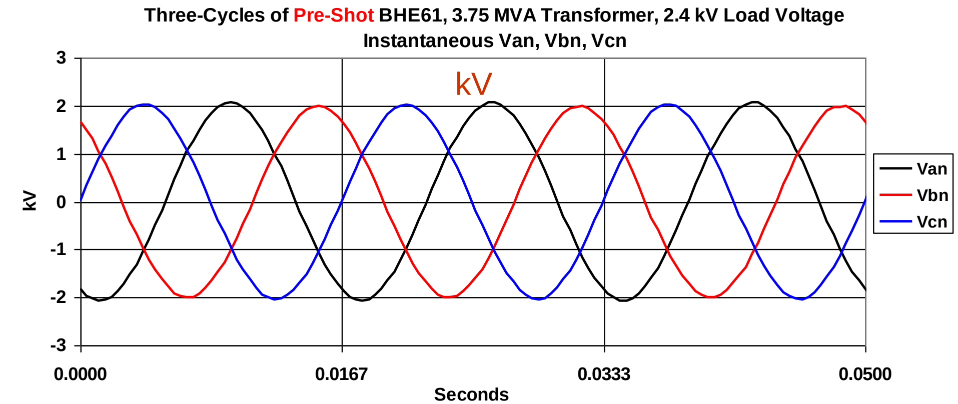
Deep-Shot 138kV Grid-Side Power Flowing Into 3.75 MVA Transformer
Three Cycles of Instantaneous Pabc = Pa+Pb+Pc
Three-phase power has strong abnormal 3rd harmonic
MW
8
7
6
5
4
3
2
1
0
8.0000
8.0167
8.0333
8.0500
Seconds

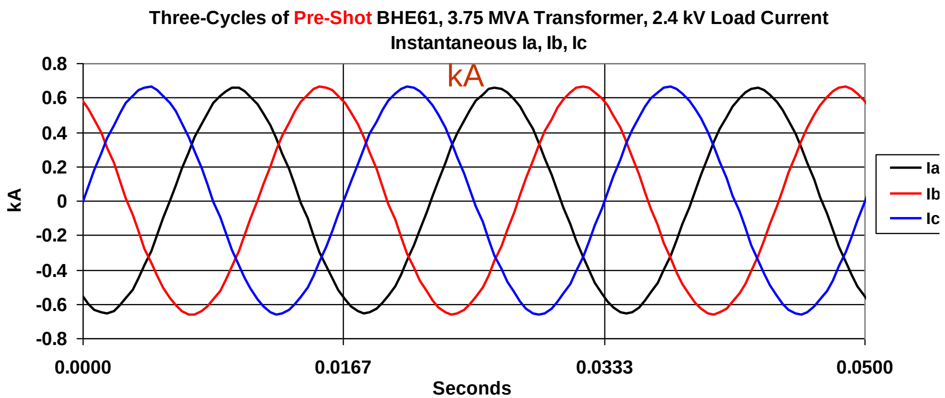
Load-Side Voltage and Current Harmonic Magnitudes

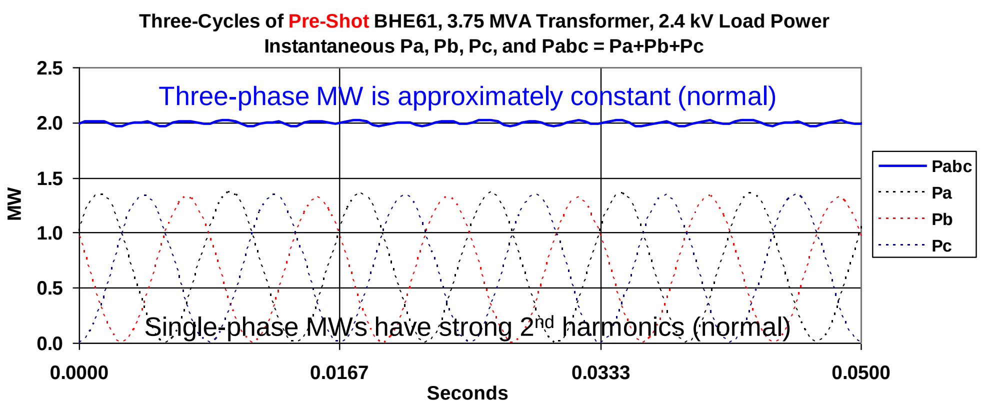




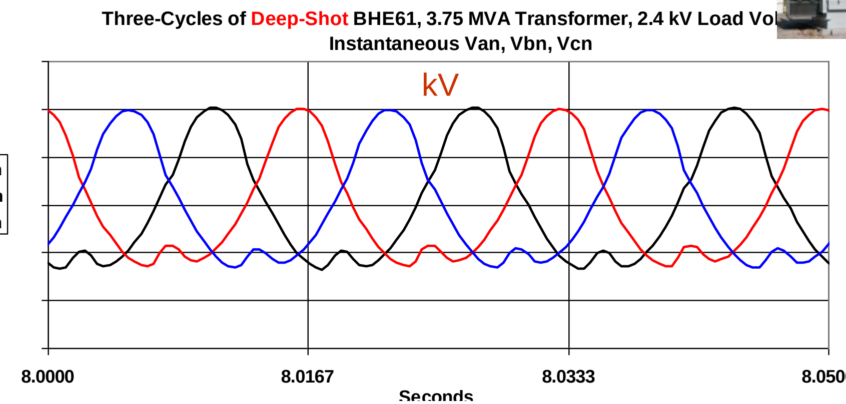
Load-Side, Pre-Shot (t = 0 sec)

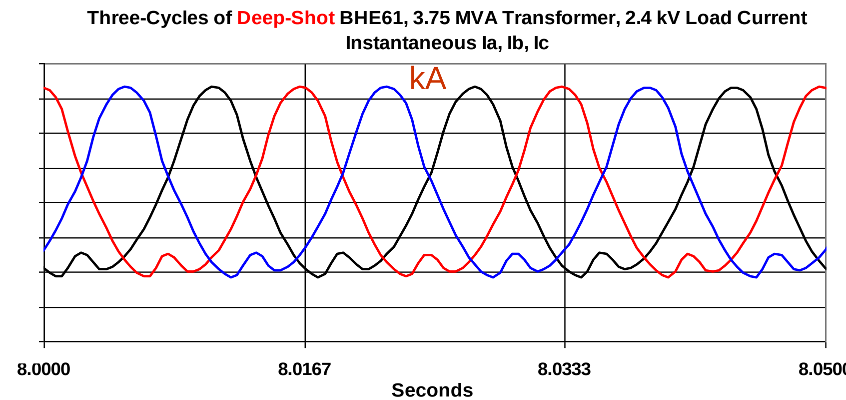


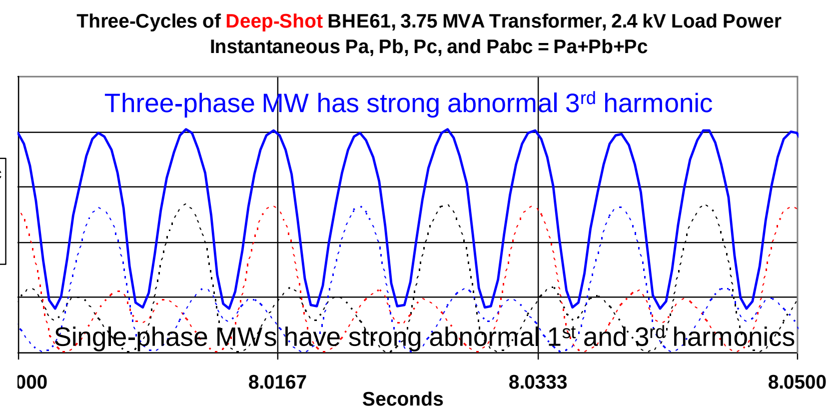




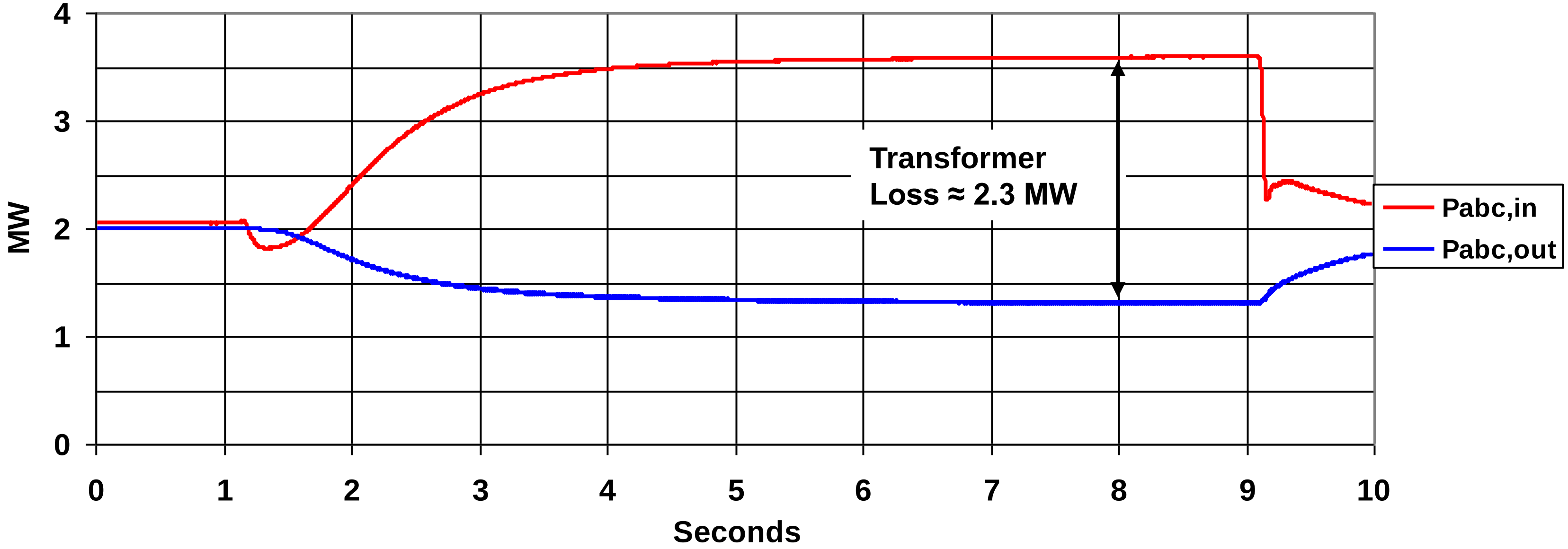
Load-Side, Deep-Shot (t = 8 sec)







Estimate of Temperature Rate of Rise Due to 2.3 MW Loss



Nameplate	
Oil,	19,654 kg
Core,	10,433 kg
Case,	12,007 kg

Specific Heats c_p	
Petroleum,	2.1
Light Oil,	1.8
Mineral Oil,	1.7
Iron,	0.45
Steel,	0.49
Copper,	0.49

$$c_p \; \frac{W(kJ)}{m(kg)T(^\circ C)},$$

$$\frac{\Delta T(^\circ C)}{\Delta t(\mathrm{sec})} = \frac{P(kW)}{c_p m(kg)}$$

$$= \frac{1000 P(MW)}{c_p m(kg)}$$

The following is the only result in this presentation **not** based entirely on measurements:

As a simple check to bound the heating problem, assume adiabatic heating where all the 2.3 MW loss is absorbed by either oil, core, or case. The corresponding temperature rate of rise would be

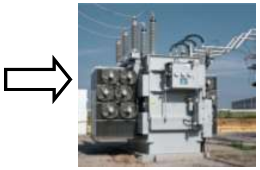
Oil, 3.9 °C per minute

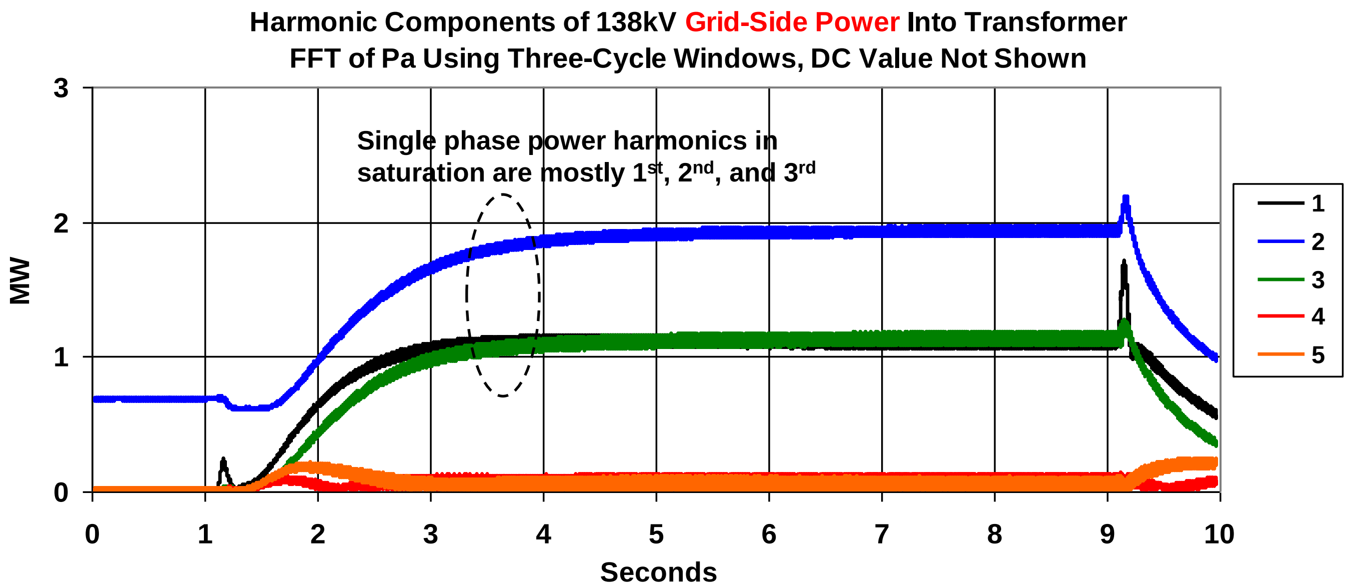
Core, 27.0 °C per minute

Case, 23.4 °C per minute

Appendix: Why does the grid Pabc flowing to the 138 kV side of the transformer have such a huge, easily recognized 3rd harmonic (i.e., 180 Hz)?

To answer, we must first understand the grid power on one phase.





- In our case, the grid-side voltage remains nearly sinusoidal.
- Core saturation creates a strong 2nd harmonic of current, that adds to the existing 1st harmonic (i.e., fundamental) current.
- Power is the product of voltage and current, and thus contains the sums and differences of voltage and current harmonics.
- Voltage harmonic 1 multiplied by current harmonics 1 and 2 yields power harmonics 1 + 1 = 2, 1 – 1 = DC, 1 + 2 = 3, 1 – 2 = -1 (same as phase shifted +1)
- In an abc balanced system, as in this case,
  non-triplen harmonics 1 and 2 for phases a,b,c add to zero, and
  triplen harmonic 3 are in phase with each other and add.
- Result – Pabc consists mostly of an average value (i.e., DC) and a **3rd harmonic**.